ABSTRACT

The equation of motion is written in quasi-natural coordinates, the tangential and normal components of which represent tendency equations for wind speed and direction respectively. An attempt is made here to determine the magnitudes of the controlling terms and to evaluate their instantaneous derivatives by means of a graphical method in order to determine the local time rate of change of the wind.

A trial wind forecast was prepared based on extrapolation methods only and was used as a standard by which to judge the feasibility of this new method.

It was found that vertical as well as horizontal advection plays an important part in the determination of the wind tendency. However, with the techniques employed here, the contributions due to vertical advection could not be measured with sufficient accuracy. The horizontal advection terms provided slightly better results but only in a qualitative sense. It is suggested that perhaps use of better techniques of analysis or smoothing would greatly improve the results.

1. INTRODUCTION

Numerical forecasting has been a goal of meteorologists even before Richardson's attempt (1922). Various theoretical bases have been used. Richardson used the equation of motion (together with the equation of continuity, equation of state, energy equation, and a conservation of water substance equation); recent investigators (Charney, Eliassen, Fjortoft, etc.) have generally used the vorticity equation in some form.

On the one hand, Richardson's use of the equation of motion itself rather than a derivative of this equation, such as the vorticity equation, seems *a priori* more reasonable. This is because it is manifestly easier to determine accurately a mapped quantity than to determine accurately its derivatives. Furthermore, if the vorticity equation is the basis for work, not only must a derived field be used, but once the vorticity field has been forecast, an integration is required for the return to the velocity field. Thus there is a differentiation which is later annulled by an integration. Obviously, both steps can contribute errors. However, as we shall see below, it is the ageostrophic part of the wind field which contributes to the changes. It is possible that by the transition to the vorticity equation in which the pressure influence appears only in the solenoidal term, work with non-significant portions of the pressure has been avoided and thus errors introduced as a result of mapping these parts of the pressure field have been avoided. Seemingly both approaches have merit. In this investigation, which supplements an earlier one performed at

Florida State University in which the vorticity equation was used (Sherman, 1952), work will be done with the equation of motion directly.

Whether one works with the equation of motion or with the vorticity equation, one must consider the possibility of introducing unwanted solutions (such as sound waves) and the question of computational stability since simplifying assumptions and computational errors are involved. Charney and others have advocated the use of a quasi-geostrophic hypothesis for these reasons. It is of interest, nevertheless, to try working with the wind field itself (rather than the pressure distribution). This field is of great interest to aviation-route forecasters for high level jet and other flights. Unfortunately, current techniques often result in 50-kt errors in the wind forecast (Campbell Orde, 1952). It is with the upper wind forecast in mind that this investigation has been carried out. The upper winds are of interest both for themselves and because it is felt that the weather patterns can probably be forecast as well or better with the flow patterns than with pressure patterns. Certainly the winds are most accurately determined from a wind analysis, especially with the recent increase in rabal and rawin observations.

The aims here are to check the orders of magnitude of the principal terms of the equations governing the time rates of change of wind speed and direction, and also to find whether or not these terms can be determined with sufficient accuracy to provide a positive aid in the wind forecast.

2. THE WIND SPEED AND DIRECTION TENDENCY EQUATIONS

If quasi-natural coordinates are used, the wind velocity may be written as

$$\mathbb{V} = c\boldsymbol{\tau} + w\mathbb{K}$$

where c is the horizontal wind speed, w is the vertical speed and

$$\boldsymbol{\tau} = -\sin\psi\,\mathbf{i} + \cos\psi\,\mathbf{j}$$

is a unit tangent to the horizontal streamline. The unit vectors $\mathbf{i}$, $\mathbf{j}$, and $\mathbb{K}$ are directed to the east, north and zenith on a spherical earth; ψ is the direction of the horizontal streamline as usually measured in meteorology (i.e. the direction <u>from</u> which the wind blows). The tangential, $\boldsymbol{\tau}$, and the normal, $\mathbb{n} = \cos\psi\,\mathbf{i} - \sin\psi\,\mathbf{j}$, components of the equation of motion will be, respectively, wind speed and direction tendency equations:

$$(1)\quad \frac{\partial c}{\partial t} = -c\frac{\delta c}{\delta s} - w\left(\frac{\delta c}{\delta z} + \frac{c}{r} - 2\Omega\cos\phi\sin\psi\right) - \alpha\frac{\delta p}{\delta s} + F_s$$

$$(2)\quad \frac{\partial \psi}{\partial t} = -c\left(\frac{\delta \psi}{\delta s} + \frac{\tan\phi}{r}\sin\psi\right) - w\left(\frac{\delta \psi}{\delta z} - 2\Omega\frac{\cos\phi\cos\psi}{c}\right) + f + \frac{\alpha}{c}\frac{\delta p}{\delta n} + F_n,$$

The usual notation is used here where

f = Coriolis parameter = $2\,\Omega\,\sin\phi$

α = specific volume

p = pressure

ϕ = latitude

Fs, Fn = tangential and normal components of frictional term.

Terms involving r, the radius of the earth, in the denominator are corrections due to the spatial variation of the unit vectors $\mathbf{i}$, $\mathbf{j}$, and $\mathbb{K}$. It follows that (1) and (2) represent a means of computing tendencies of wind speed and direction respectively since the terms on the right side of the equations can be evaluated, at least theoretically.

From simple order-of-magnitude computations, it can be seen that all correction terms due to the curvature of the earth are extremely small. They will be neglected here. Also terms involving products of w, the vertical wind speed, and Ω, the angular speed of the earth's rotation, will be small and here neglected. Because of a lack of knowledge of the viscous terms, Fs and Fn, work will be done at a level where they are believed to be small and thus negligible. The quantity $\alpha\frac{\delta p}{\delta s}$ may be replaced by $g\frac{\delta h}{\delta s}$, where h is the height of an isobaric surface. Equations (1) and (2) then become

$$(3)\quad \frac{\partial c}{\partial t} \approx -c\frac{\delta c}{\delta s} - w\frac{\delta c}{\delta z} - g\frac{\delta h}{\delta s}$$

and

$$(4)\quad \frac{\partial \psi}{\partial t} \approx -c\frac{\delta \psi}{\delta s} - w\frac{\delta \psi}{\delta z} + \left(f + \frac{g}{c}\frac{\delta h}{\delta n}\right).$$

In both tendency equations, essentially three terms remain. They are what will be called the (horizontal) advective term, the vertical velocity term, and the ageostrophic term respectively.

It is observed that temperate zone wind systems usually move from west to east at a speed slower than the wind. Thus the advective term in each of equations (3) and (4) must be opposed, to some extent at least, by one or more of the remaining terms. The choice of these has so far been narrowed to the ageostrophic and vertical velocity terms. It will often be the case that while vertical shears of the wind speed are significant, no appreciable turning of the wind is present [see, for example, Charney, Fjortoft and von Neumann (1950)]. In the cases dealt with here, it was found that the turning of the wind at the working level (16,000 ft) was generally of the order of 10°/4000 ft or less. This turning could not be analyzed since winds are reported only to this accurracy. Hence the terms which must be considered

in addition to the advective term must be either or both the ageostrophic and vertical velocity terms in the case of the speed tendency equation, and the ageostrophic term in the case of the direction tendency equation. It should be noted that a 10 cm/sec vertical velocity (more than average) together with a turning of the wind of 10°/4000 ft will result in a change of less than 10°/3 hrs in the wind direction; hence the vertical velocity term of the direction tendency equation, neglected of necessity because it cannot be analyzed, is not a dominant one.

This narrowing of the choice of terms to the (horizontal) advective term, the ageostrophic term and, in the case of the speed tendency, perhaps the vertical velocity term is in accord with the experience of other investigators. For example, Riehl and Jenista (1952) reported that in their work the ageostrophic term of the speed tendency was significant and invariably opposed to the (horizontal) advective term.

Initially it was felt that the vertical velocity terms, whether large or small, would perhaps be systematic in certain regions (for example, the lee of the Rocky Mountains). Such non-random effects should be taken into account even if they are relatively small. Because of the complexity of the vertical velocity computation, which would affect both the accuracy and the operational feasibility of the computation, it was hoped that, should this term be significant, perhaps some average map of it could be used. This could occur in the event that the patterns were largely orographically determined or consisted of an orographic part (this would appear in the mean map)

and a synoptic part which would correlate with the horizontal wind patterns. Aside from the question of whether or not these vertical velocity terms can be dealt with on a day to day basis, it is desirable to look at their order of magnitude.

The ageostrophic terms of both equations were clearly the prime candidates for the role of counterbalance to the advective terms. These ageostrophic terms will be hard to compute accurately, for a simple calculation will show that contour differences along a streamline must be measured to within roughly 85 ft/5° lat to compute the ageostrophic contribution to the speed tendency to within 10 kts/3 hrs. Similarly, contour differences along the normal must be measured to within 55 ft/5° lat in order to compute an ageostrophic contribution to the direction tendency of 10°/3 hrs. Thus small errors in the analysis of the streamline and contour fields lead to very large discrepencies in the tendency fields. However, this very sensitivity demonstrates the importance of these terms. It is certain that indrafts of the order of 10° to 30° or more do occur. With wind and geostrophic wind speeds of the order of 50 kts, a 10° indraft would imply a 10 kt/3 hr ageostrophic contribution to the speed tendency.

3. THE SYNOPTIC SITUATION

The choice of the period over which to test the calculations was not random. The week commencing on the 19th of April, 1950 was a "Meteorological Week", during which special effort was made to obtain a maximum number of observations. For the test in this investigation two days were chosen, the 19th and 20th of April from this week, and calculations at 0300Z and 1500Z each day were made. To minimize the

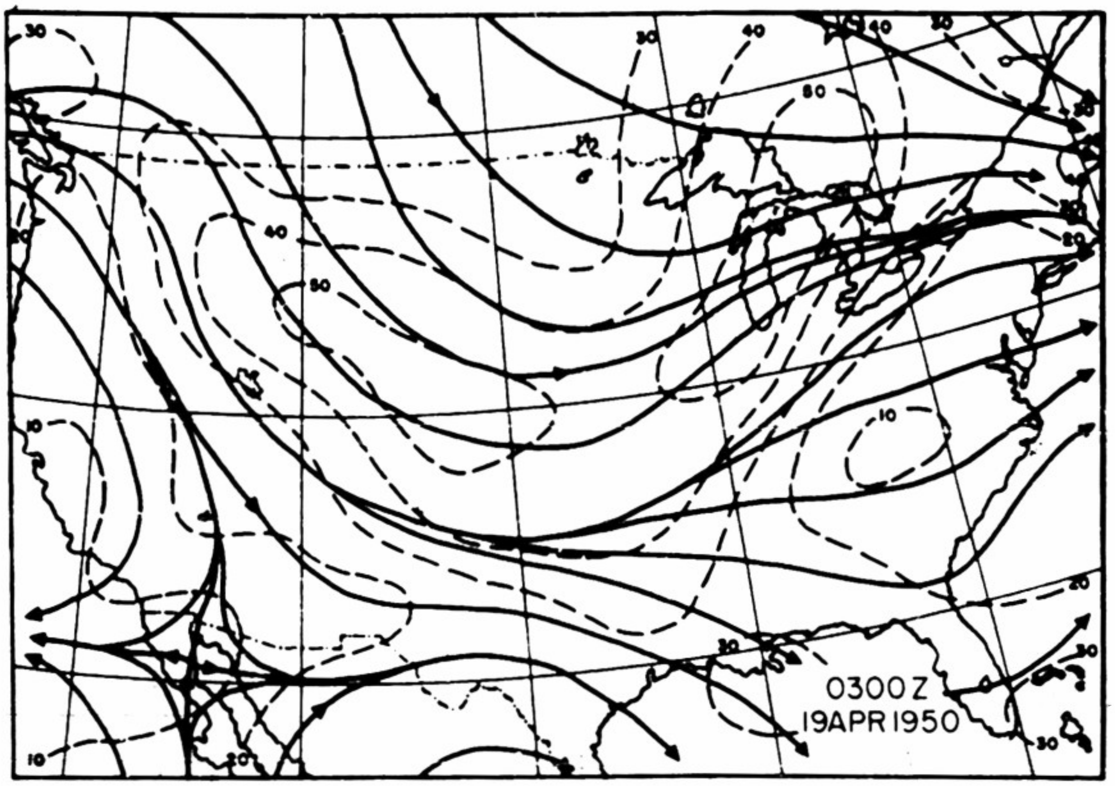

Figure 1. 16,000 foot streamline-isovel map

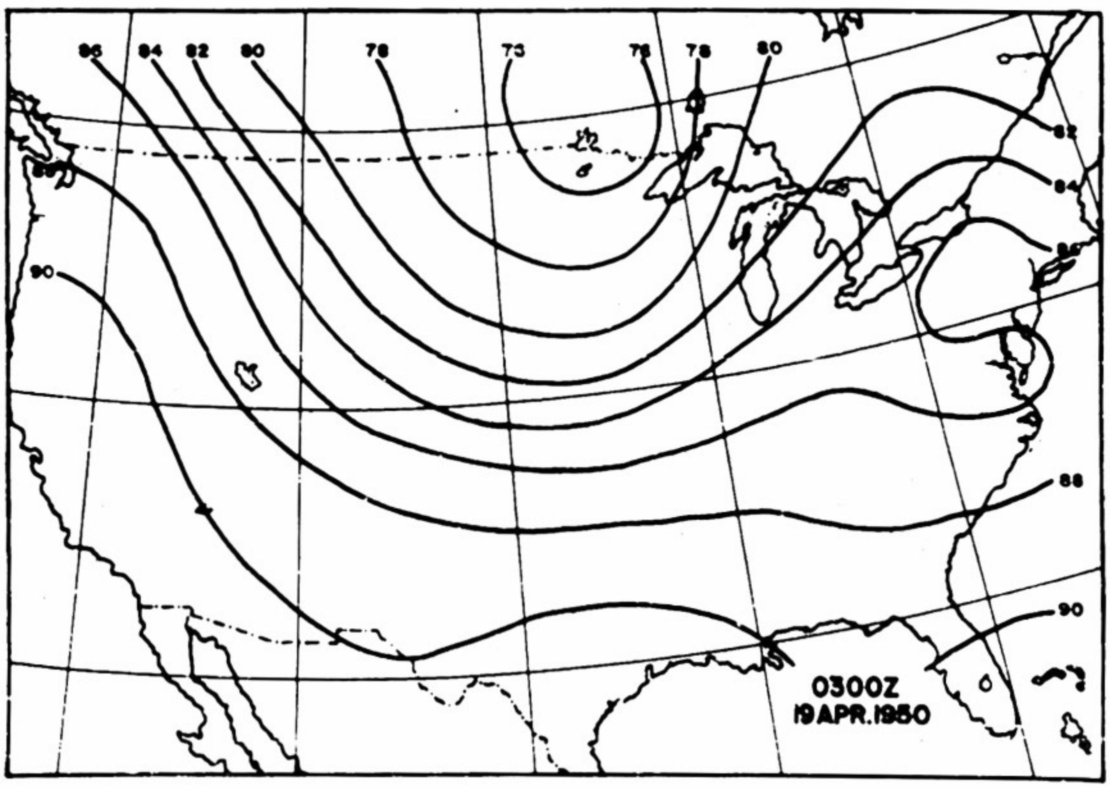

Figure 2. 500 millibar contour chart

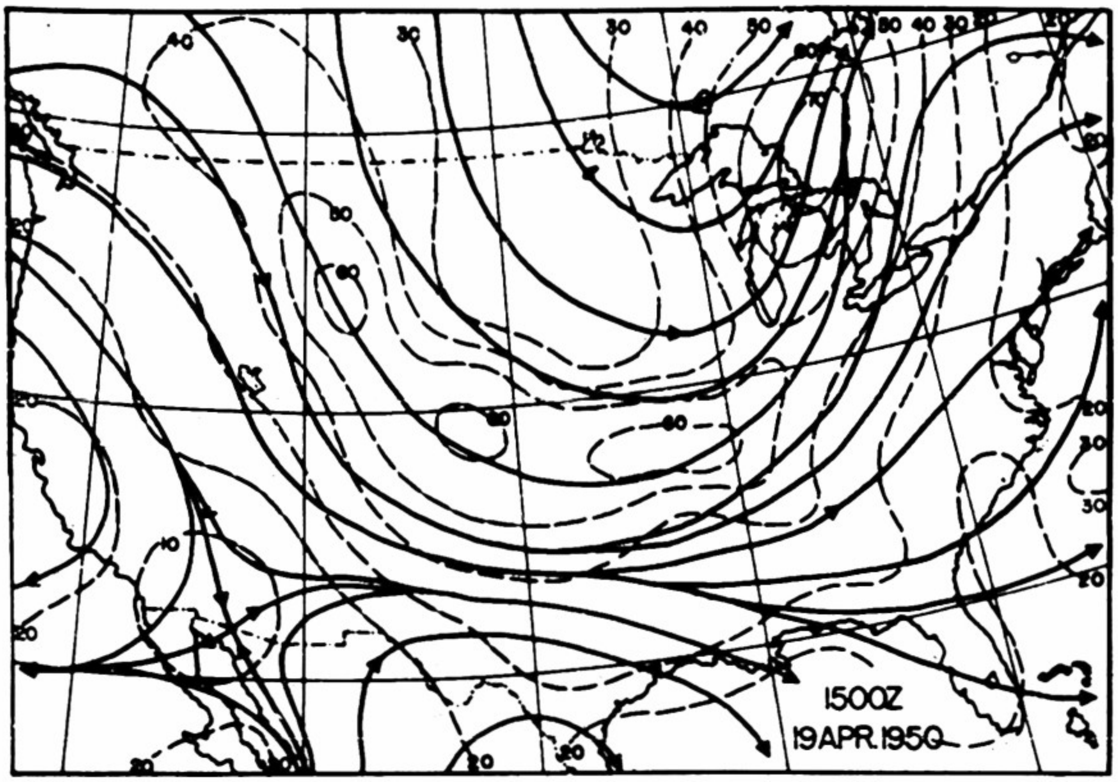

Figure 3. 16,000 foot streamline-isovel map

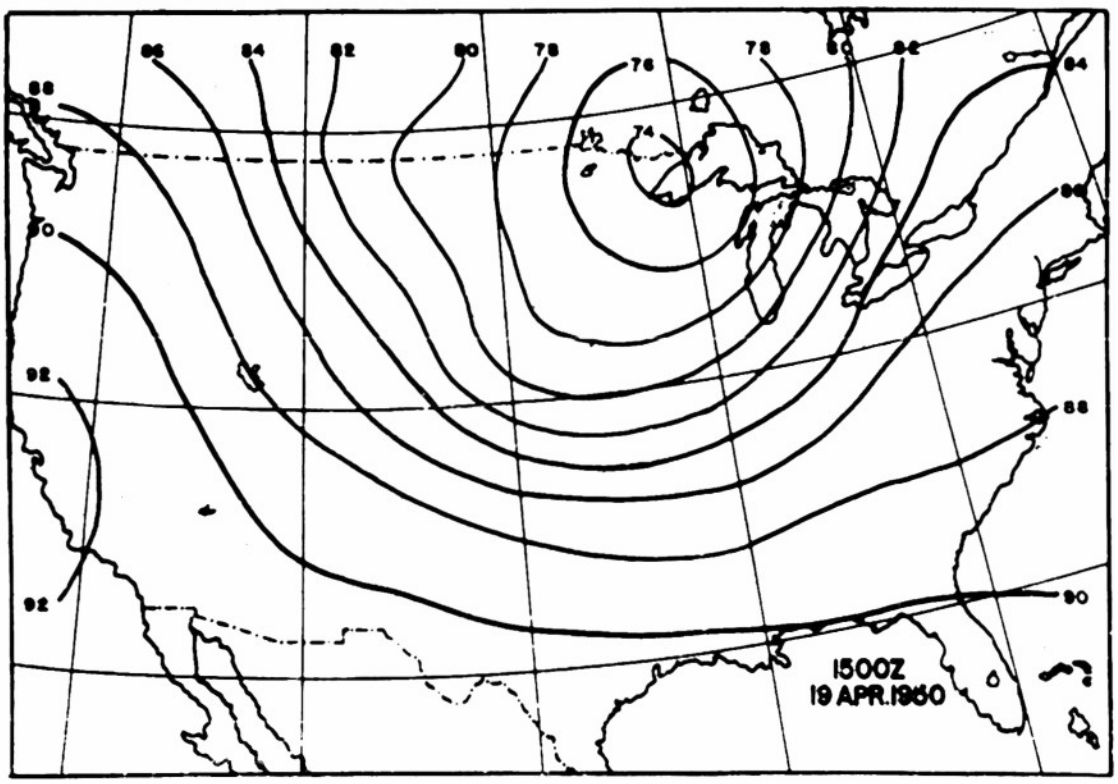

Figure 4. 500 millibar contour chart

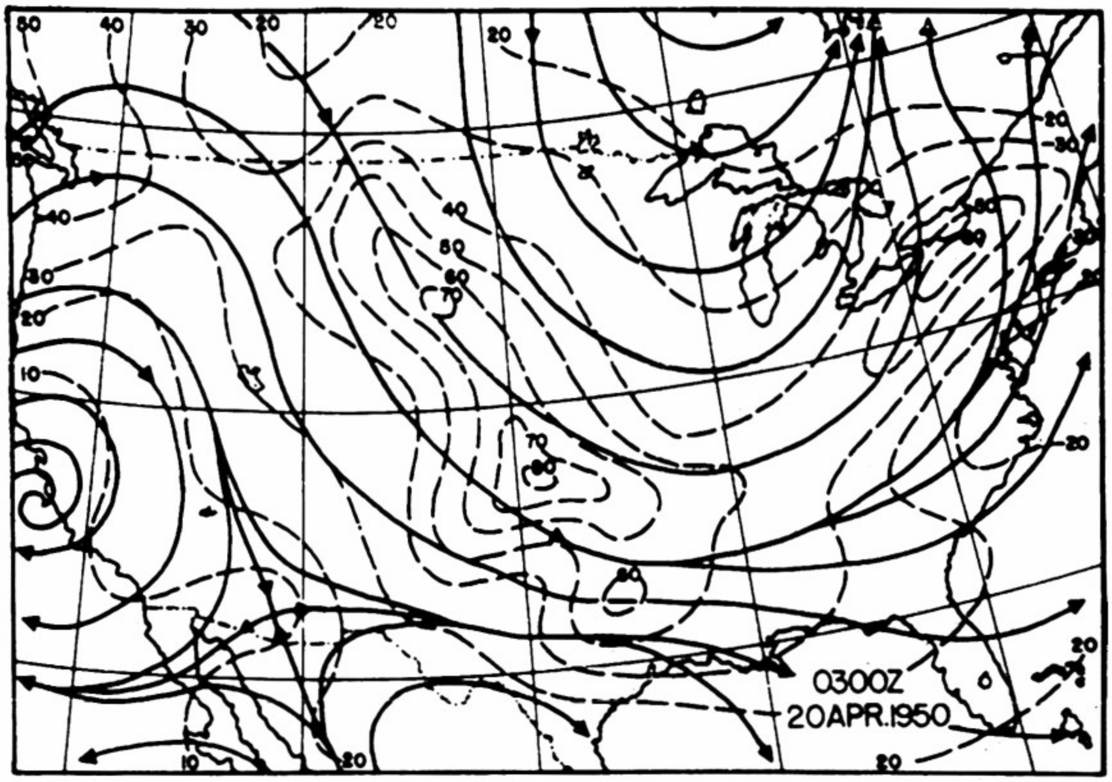

Figure 5. 16,000 foot streamline-isovel map

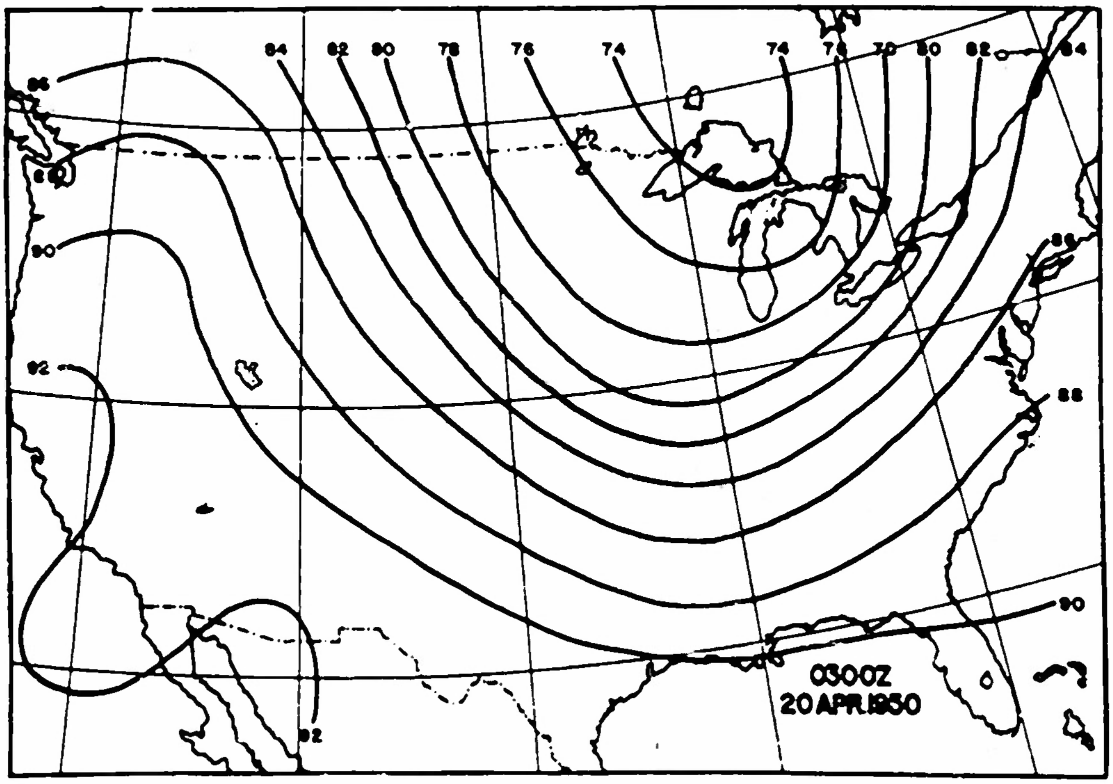

Figure 6. 500 millibar contour chart

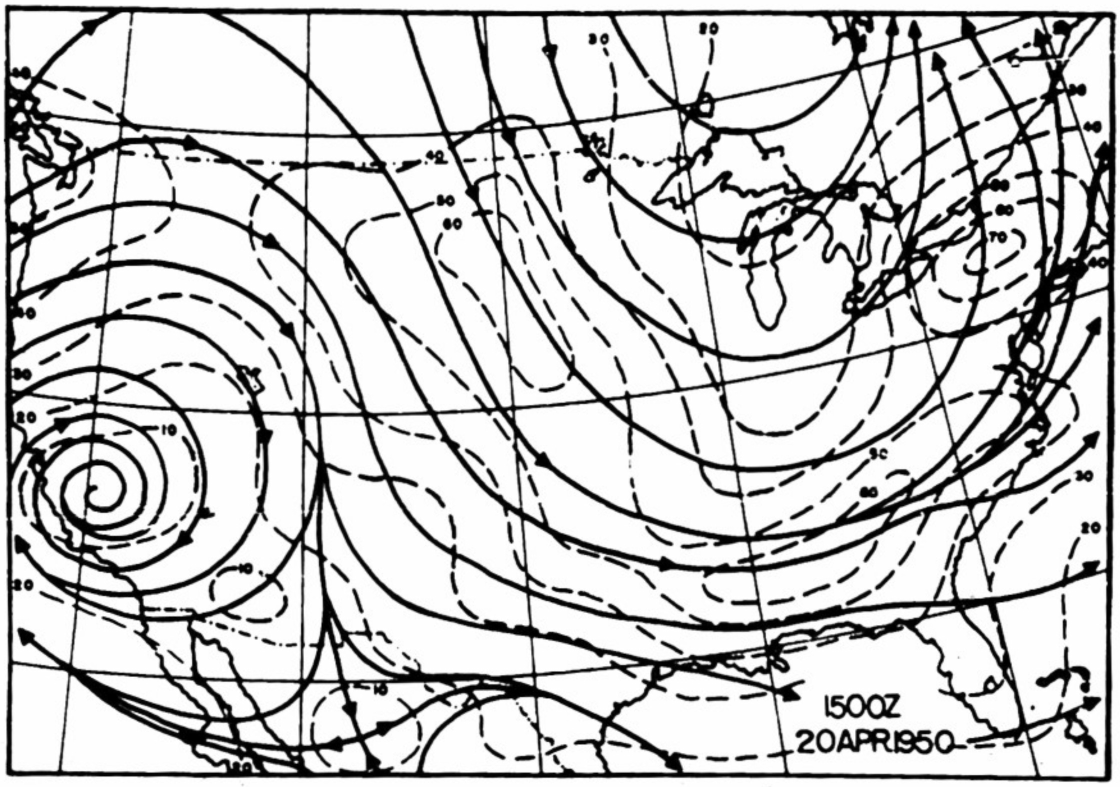

Figure 7. 16,000 foot streamline-isovel map

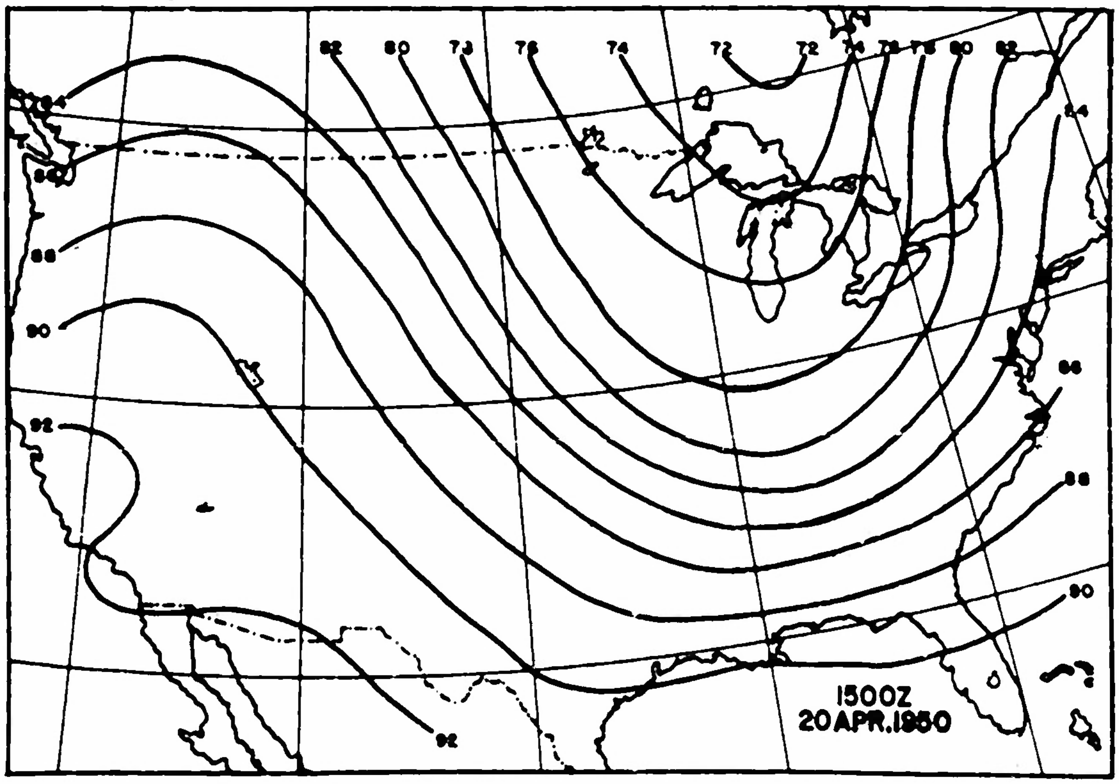

Figure 8. 500 millibar contour chart

effects of friction, a level high over the Rocky Mountains with a sufficiently dense network of observations was sought. Originally it was planned to use the 18,000 ft level, primarily because it is the highest level for which winds are still reported 2000 ft above and below. However, it was found that the density of observations dropped off severely at 18,000 ft, so the 16,000 ft level was finally chosen.

Presented in figs 1-6 are the 16,000 ft streamline-isovel maps and the 500-mb contours for the period of this investigation.

The purpose here was two-fold: to investigate the orders of magnitude of the various terms, and to see if computations of the speed and direction tendencies could be made with sufficient accuracy to aid in the wind forecast. For this latter part of the investigation, forecast maps, involving extrapolation methods only, of the isogon and isovel fields were made for the period ending at 1500Z on the 20th. This choice of forecast period gave two history maps and a verification map. Only if the speed and direction tendencies led to an improvement over this forecast would they be of predictive value.

4. THE COMPUTATIONS

To compute the advection of both wind speed and direction, the respective maps were superimposed over the corresponding streamline chart and moved with the speed of the wind forward and backward in time, three hours each way, along the streamlines. These two fields were then subtracted to obtain a six-hour tendency. This method was used to center the advective term about the observational time and to

prevent "overtaking" in regions of intense speed gradients. "Overtaking" means that in regions of high wind speeds isogons and isovels will be advected beyond adjoining regions where the speed is less. Hence, in a 6-hr movement in one direction for example, overlapping might occur.

In the computation of the vertical velocity, a kinematic method similar to that described by Panofsky (1945) was employed. Pressure weighted vector sums of the winds up to 16,000 ft were computed. The horizontal divergence of the resulting vector field was then computed by means of an adaptation of the "Graham computer" (Graham, 1953). The vertical shears were obtained by subtracting the 18,000-ft wind speed observations from those at 14,000 ft. Graphical multiplication was then used to obtain the products of the shears with the vertical velocity.

To compute the ageostrophic component of the speed tendency equation, a carefully analysed 500-mb contour map (drawn from pressure values only) was differentiated along the 16,000-ft streamlines. In the direction tendency equation, the ageostrophic contribution computed by graphical addition of the Coriolis parameter, f, to the product of gravity with the derivative of 500-mb contours (analysed for every 100 ft) along the left hand 16,000-ft normals. The various space derivatives were computed graphically.

For each 12 hourly map time, the following charts were constructed:

A. Basic charts

(1) isogon analysis

(2) streamlines

(3) left hand normals

(4) isovel analysis

(5) 500-mb contour analysis

B. Speed tendency

(6) advective estimate of c(t + 3 hr) ← (advection along streamlines) ⟵ (2), (4)

(7) advective estimate of c(t - 3 hr) ← (advection along streamlines) ⟵ (2), (4)

(8) centered (at time t) 6 hr advective rate of change of c (graph. subtr.) ⟵ (6), (7)

(9) $\frac{\delta h}{\delta s}$ ⟵ (graph. diff.) < (2), (5)

(10) $-g\frac{\delta h}{\delta s}$ ← (interpolation) —— (9)

(11) $\frac{\delta c}{\delta z}$ ← plotted and analyzed from 14,000 and 18,000 ft signals

(12) $-\int_{\mathrm{sfc}}^{500'} \frac{V_H\,\delta p}{(fg)_H}$ ← computed vectorially at each station and analyzed.

(13) $\omega_{500} \simeq \nabla_H \cdot \left(-\int_{\mathrm{sfc}}^{500'} \frac{V_H\,\delta p}{(fg)_H}\right)$ ← Graham computor

(14) $-\omega\frac{\delta c}{\delta z}$ ⟵ (graph. mult.) < (11), (13)

(15) $-c\frac{\delta c}{\delta s} - \omega\frac{\delta c}{\delta z}$ ⟵ (graph. add.) < (8), (14)

(16) $\frac{\partial c}{\partial t} \simeq -c\frac{\delta c}{\delta s} - \omega\frac{\delta c}{\delta z} - g\frac{\delta h}{\delta s}$ ⟵ (graph. add.) < (10), (15)

C. Direction tendency

(17) advective estimate of ψ(t + 3 hr) ⟵ (advection along streamlines) < (1), (2), (4)

(18) advective estimate of ψ(t - 3 hr) ⟵ (advection along streamlines) < (1), (2), (4)

(19) centered (at time t) 6 hr advective change in ψ_H (graph. subtr.) < (17), (18)

(20) $\frac{\delta h}{\delta n}$ ⟵ (graph. diff.) < (3), (5)

(21) $\frac{g}{c}\frac{\delta h}{\delta n}$ ⟵ (graph. mult.) < (20), (4)

(22) $f + \frac{g}{c}\frac{\delta h}{\delta n}$ ⟵ (graph. add.) < (21), (common f map)

$$(23)\ \frac{\partial\psi}{\partial t} \approx -\frac{\delta\psi}{\delta s} + \left(f + \frac{g}{c}\,\frac{\delta h}{\delta r}\right) \longleftarrow (\text{graph. add.}) \begin{cases}(19)\\(22)\end{cases}$$

<u>Results of the computations:</u> Although the wind field and pressure contours were analysed independently, in those regions where a relatively dense network of signals was available for both, they were in general agreement. In other regions it was obvious that gross errors had occurred.

It is possible to check the wind and pressure analyses for consistency in terms of the sign of the expected contributions from the various terms of the speed- and direction-tendency equations. If the ageostrophic term is to oppose (and be dominated by) the advective term, then in regions where the streamlines cross from high to low isovel values (i.e. where the wind, blowing through systems, experiences a deceleration), the streamlines should cross from low to high pressure contour values. This can be readily checked from the wind and pressure analyses.

The area over which all the analyses invariably extended is indicated in fig 9 on page 17. Within this area it was felt the results ought to be tested. It turns out that over most of the test area, for each of the first three map times, the streamlines were found to cross the isovels and pressure contours so as to result in the advective and ageostrophic terms being in agreement rather than opposition. However, on the map for 1500Z of the 20th, these terms are in opposition where the streamlines exit from the speed maximum over the southeastern United States. This doubt about the relationship between the advective and ageostrophic terms (as computed from the ana-

lyses in this investigation) diminishes hopes for sufficiently accurate computations for forecasting, but makes more desirable the checking of other terms of the equation, particularly the vertical velocity one. However, further computations were made, seeking to determine, at least, the order of magnitude of the computed contributions for each term.

The speed-advection terms gave tendencies ranging generally between $\pm$ 25 kts/6 hrs. These computations, by virtue of their simplicity, are considered here to be quite reliable. Furthermore, they would yield computed motions of the systems greater than those actually observed, as expected.

The vertical velocity terms of the speed tendency gave contributions ranging generally between $\pm$ 30 kts/6 hrs or less, save on one map--0300Z/19th-- for which extreme vertical velocities were measured. On this map, contributions to the speed tendency due to this term ranged between + 50 and - 40 kts/6 hrs. In general, then, the vertical velocity term was of the same size (or was even a little greater) than the horizontal advective term!

Ageostrophic contributions to the speed tendency ranged generally between $\pm$ 40-50 kts/6 hrs, with the northeast corner of the check area generally giving high values; on one map (0300Z/20th), values to greater than 100 kts/6 hrs were computed in this corner. The tangential derivatives of the contours ($\frac{\delta h}{\delta s}$ - Map 9 for each time) were computed for 100 ft/5° lat intervals. An isoline value of one, then, corresponded to more than 22 kts/6 hrs! Certainly the speed ten-

The advective direction tendencies, again, seemed quite reliable. They generally ranged between $\pm$ 40°/6 hrs (but reached 70°/6 hrs on one map). The ageostrophic terms $\left(f + \frac{g}{c}\frac{\delta h}{\delta n}\right)$ ranged between $\pm$ 130°/6 hrs. Again, these terms did not seem to oppose each other systematically.

It was quite obvious at a relatively early stage that, by use of the basic streamline and pressure analyses made here, the computed tendencies would not be at all useful. Since there was a strong *a priori* belief that the systems move generally with the wind, but not as fast as the wind (i.e. that the advective terms should dominate), it was next considered whether or not a qualitative use of the advective contributions to the speed and direction tendencies would be possible. There was hope for this both because of this *a priori* belief and because of the presumed reliability of these advective tendencies. A trial wind forecast was made by extrapolation methods only and used as a basis for verification.

A trial wind forecast: The period from 0300Z/20 to 1500Z/20 was chosen for a trial forecast. This was from the third to the last map; it provided two history maps and a verification map for the forecast. The isogons and isovels were first forecast by simple extrapolation. The results are shown in figs 10-14.

The prognostic isogon chart was made as follows: The 170° inflection point (isogon center) north of Lake Ontario was extrapolated both with respect to intensity and position; so too were the singular points in the southwest. The westernmost singular point

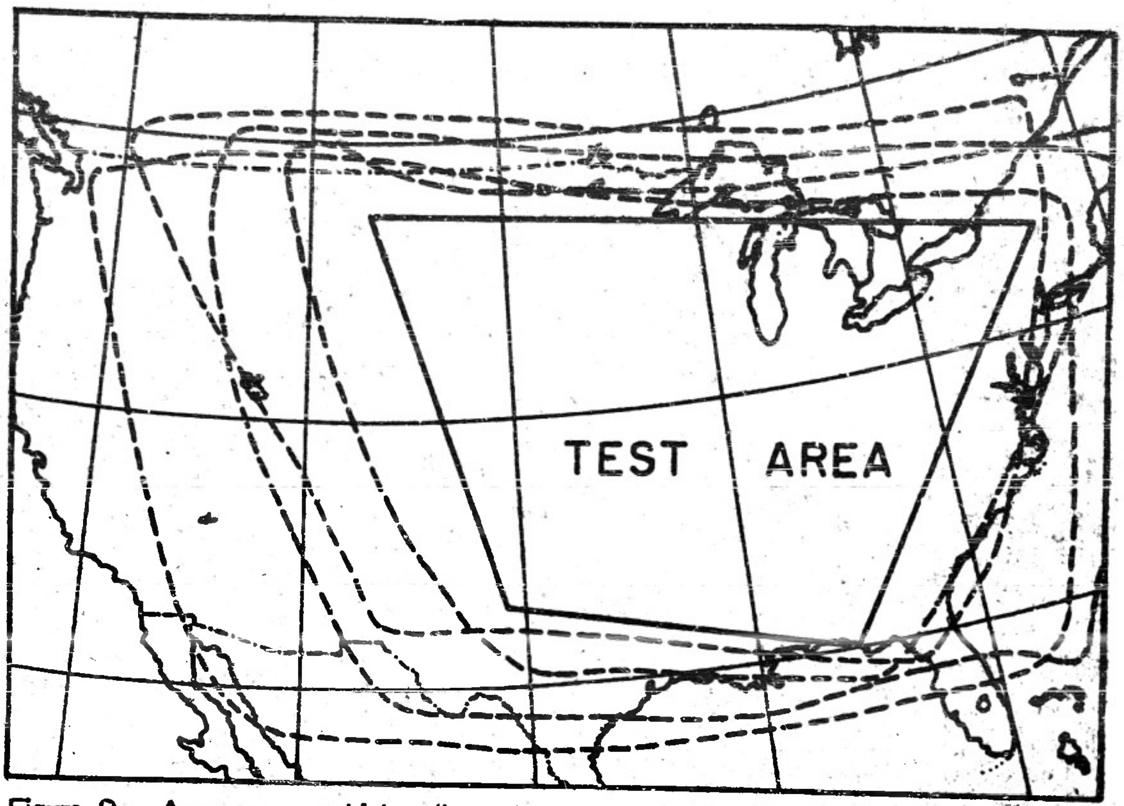

Figure 9. Area over which all analyses extended. Dashed lines indicate borders of final computations.

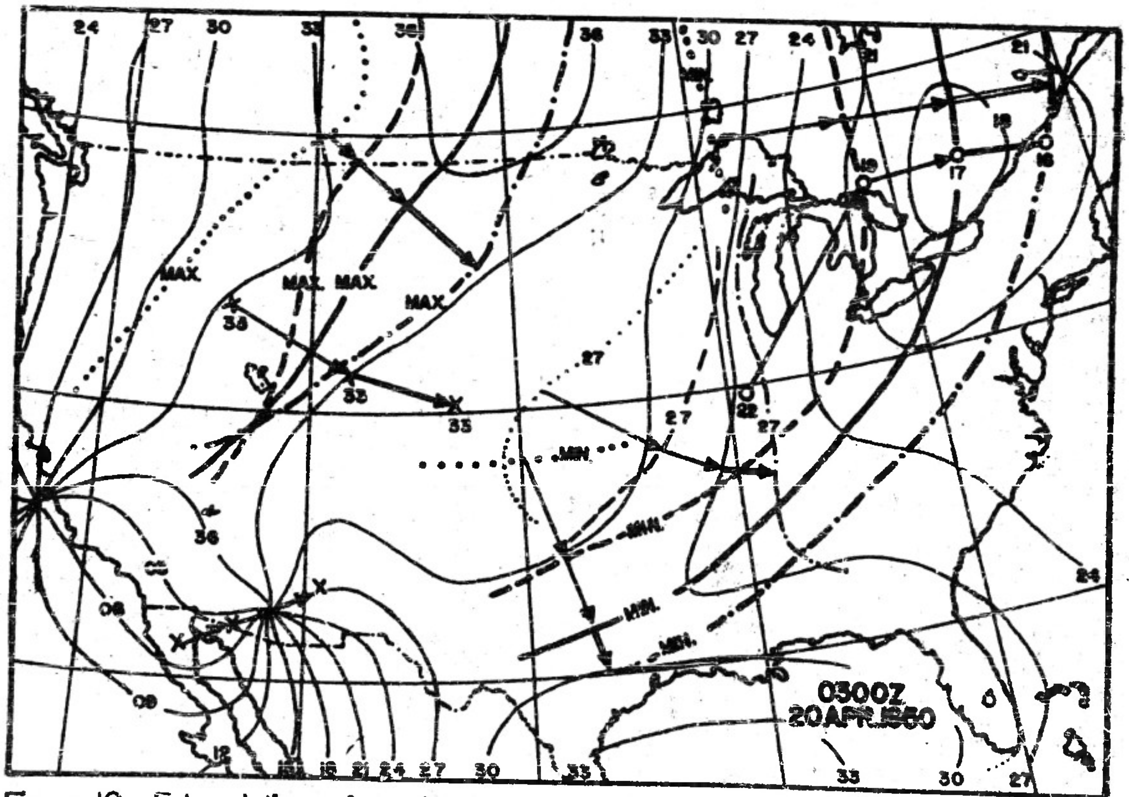

Figure 10. Extrapolations for trial isogon forecast. Legend: ···0300Z/19; ---1500Z/19; —map time; --forecast 1500Z/20

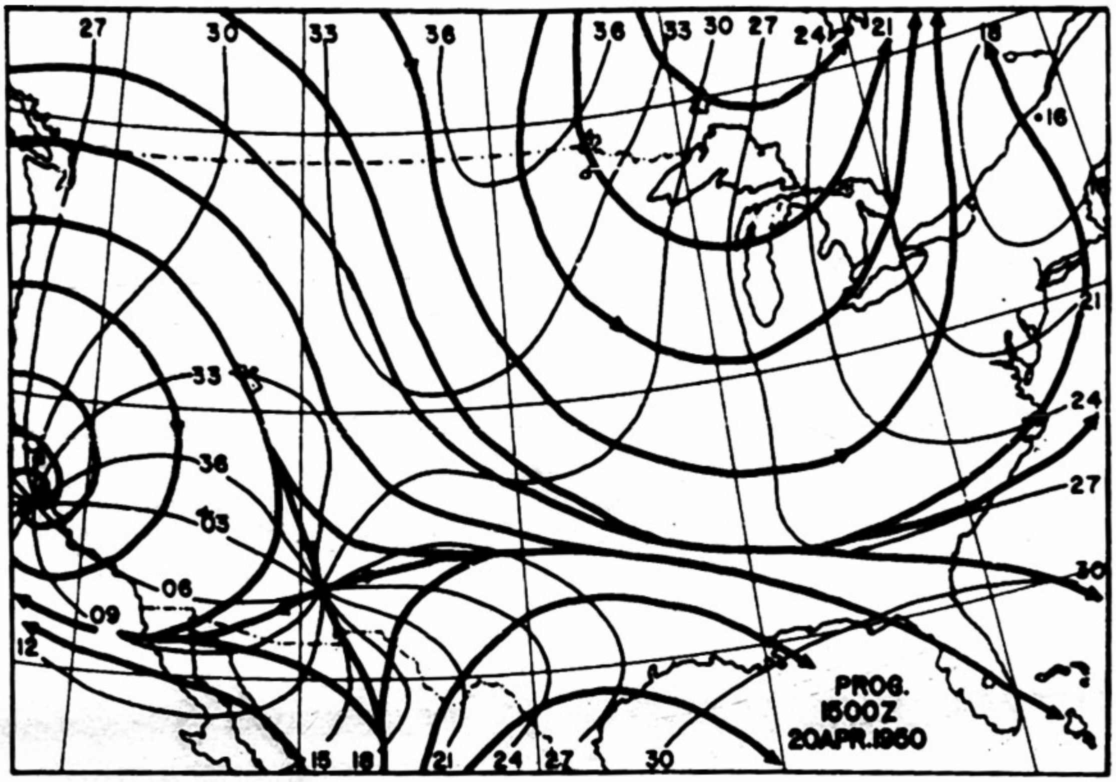

Figure 11. Forecast isogon map with streamlines.

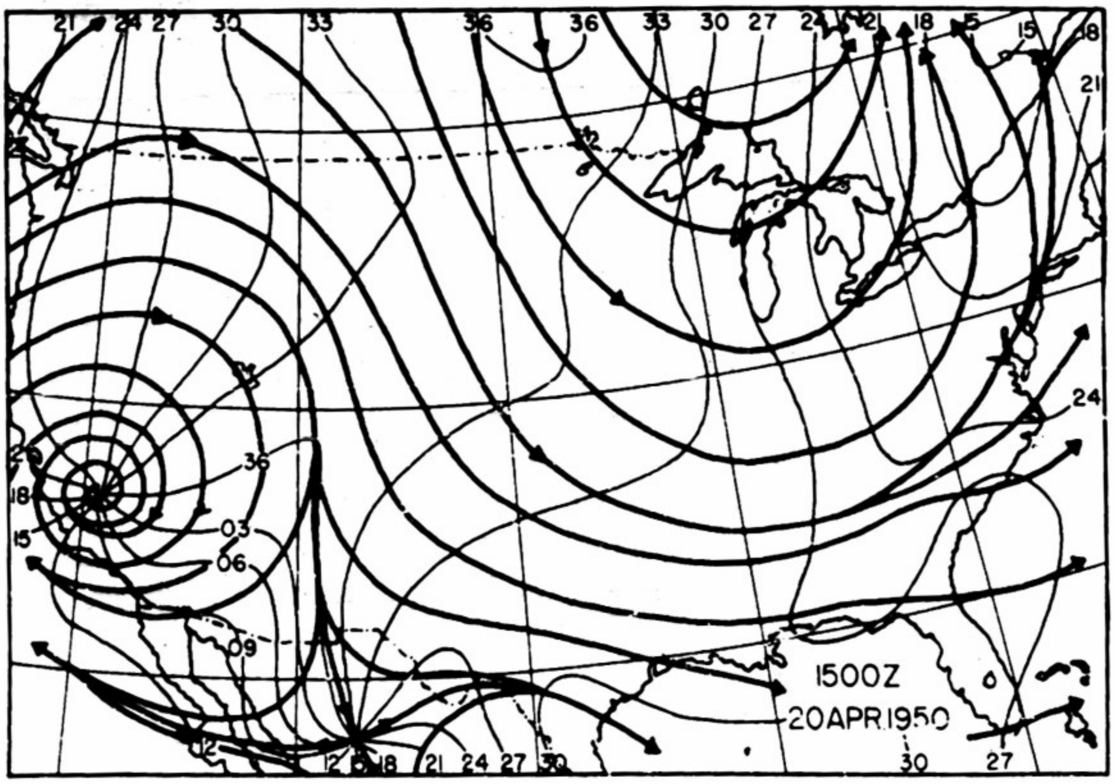

Figure 12. Verification isogon map with streamlines.

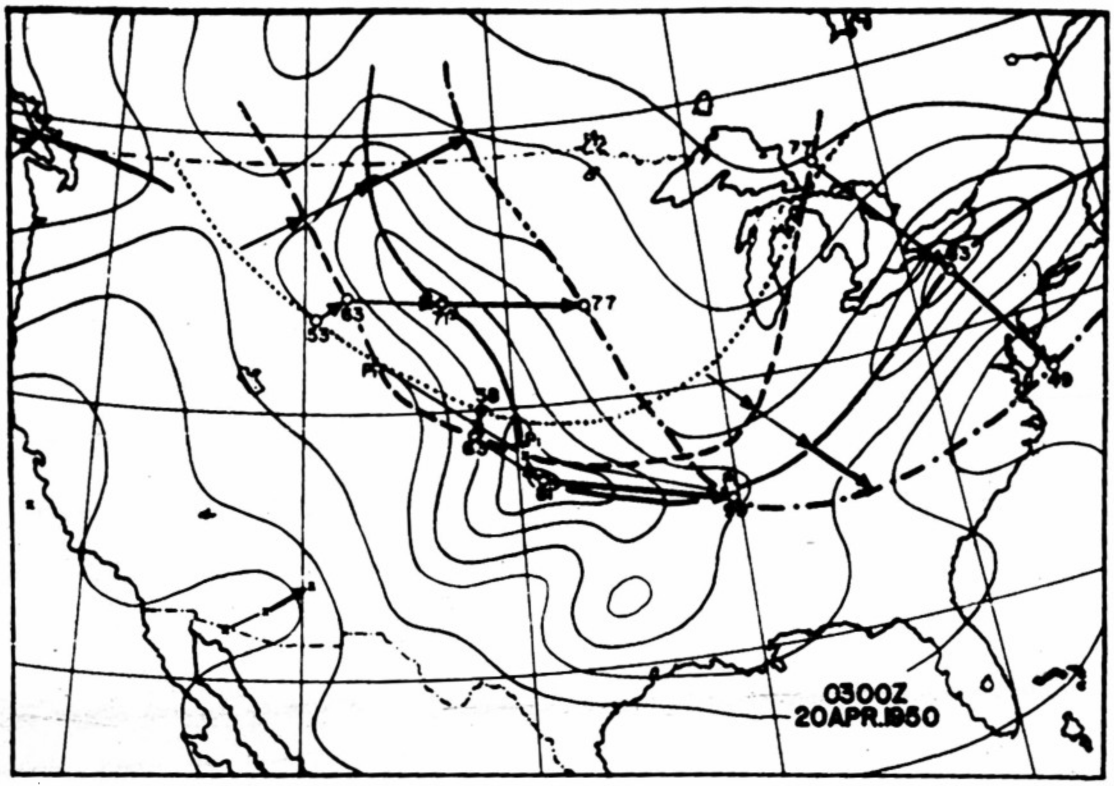

Figure 13. Extrapolations for trial isovel forecast. Legend: ···0300Z/19; ---1500Z/19; —— map time; -·-forecast 1500Z/20

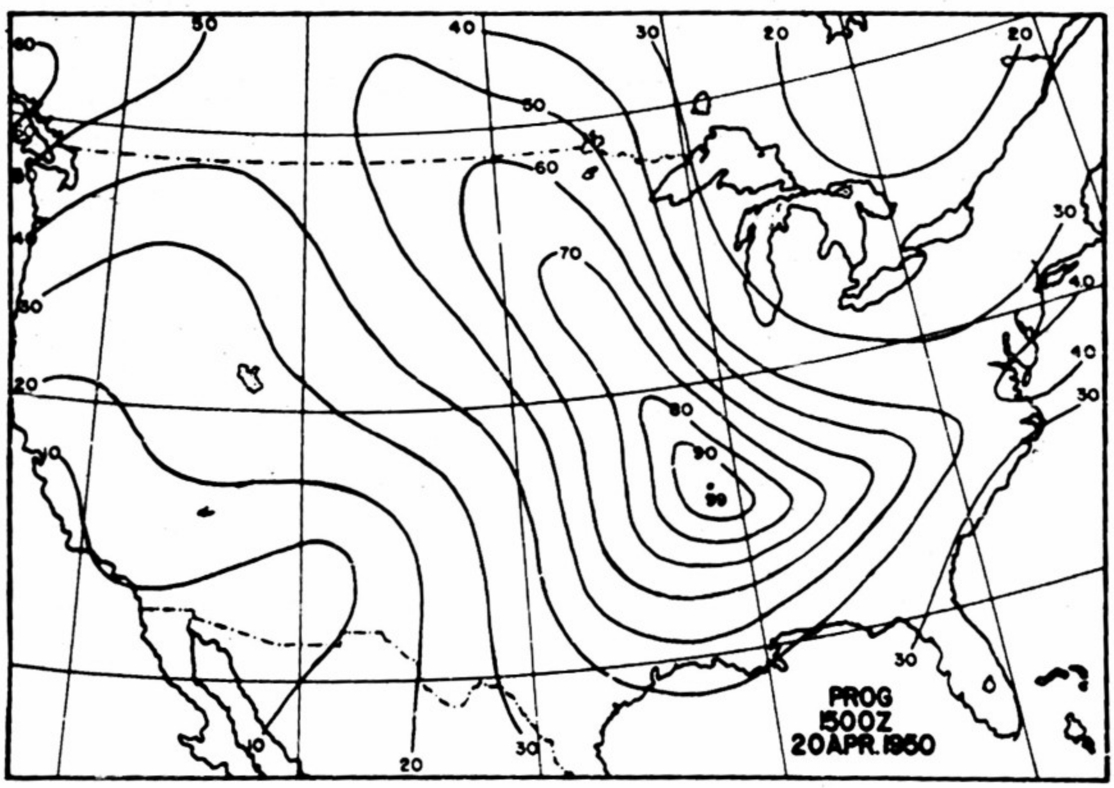

Figure 14. Forecast isovel map.

had appeared on but one map and was forecast not to move. The orientation with respect to the first of these points of the 360° isogon was extrapolated, as was the orientation of the 270° isogon in the case of the second. These were taken to be reliable isogons for this purpose (because they were straight and not close to others). The 270° isogon in the central Mississippi valley was then extrapolated as shown; also, the intersection of successive positions of the 330° isogon in the Idaho-Wyoming area was moved as indicated. Finally the axes of relative maxima and minima of the isogon field in the mountain states and through the 170° center north of Lake Ontario respectively were extrapolated. All of these preliminary extrapolations are shown on fig 10. The resulting forecast isogon map is shown in fig 11; streamlines (which are completely determined by the isogons) have been added. Fig 12 is the corresponding verification map.

The wind speed forecast map for the period 0300Z/20 to 1500Z/20 was made as follows: The jet axis was extrapolated linearly in the Montana area. A pivot (p_1) of the axis was located by extrapolation of intersecting points of successive jet positions. Also the various speed maxima were extrapolated and the forecast jet drawn through them. Intensities of these speed maxima were also extrapolated. The zero speed values were marked to agree with the direction forecast maps and 10-kt isovels were drawn approximately the same size as those appearing on the previous map. The 30-kt isovel in the central mountain states was more or less stationary. A bisector between its successive positions was drawn and a segment of the isovel was

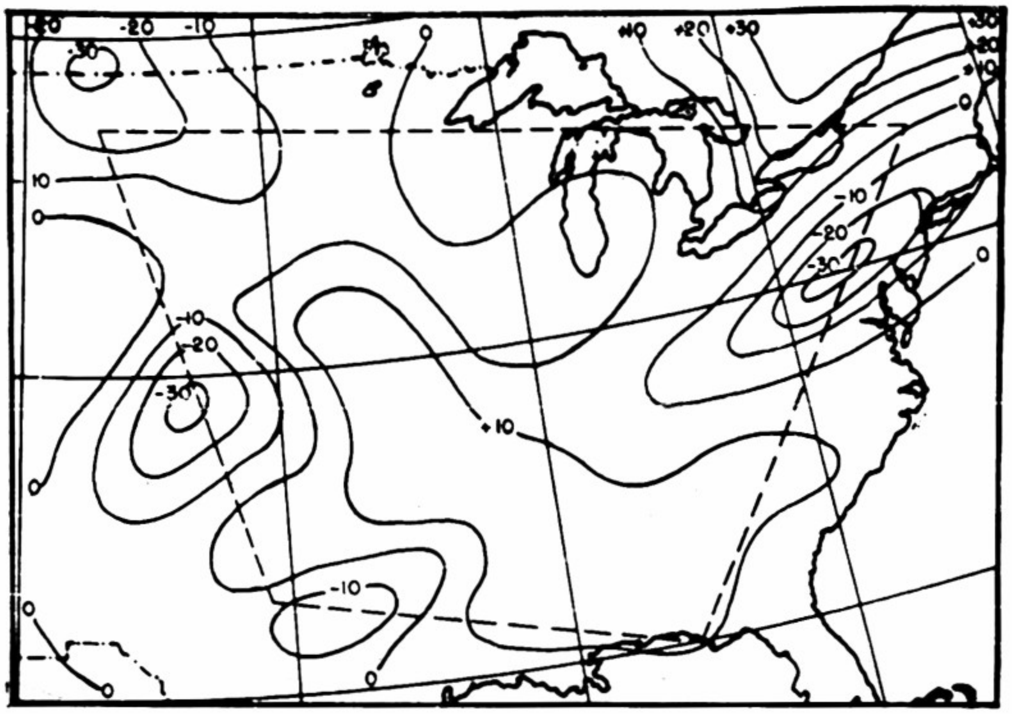

Figure 15. Advective speed tendency chart in units of knots/6 hours.

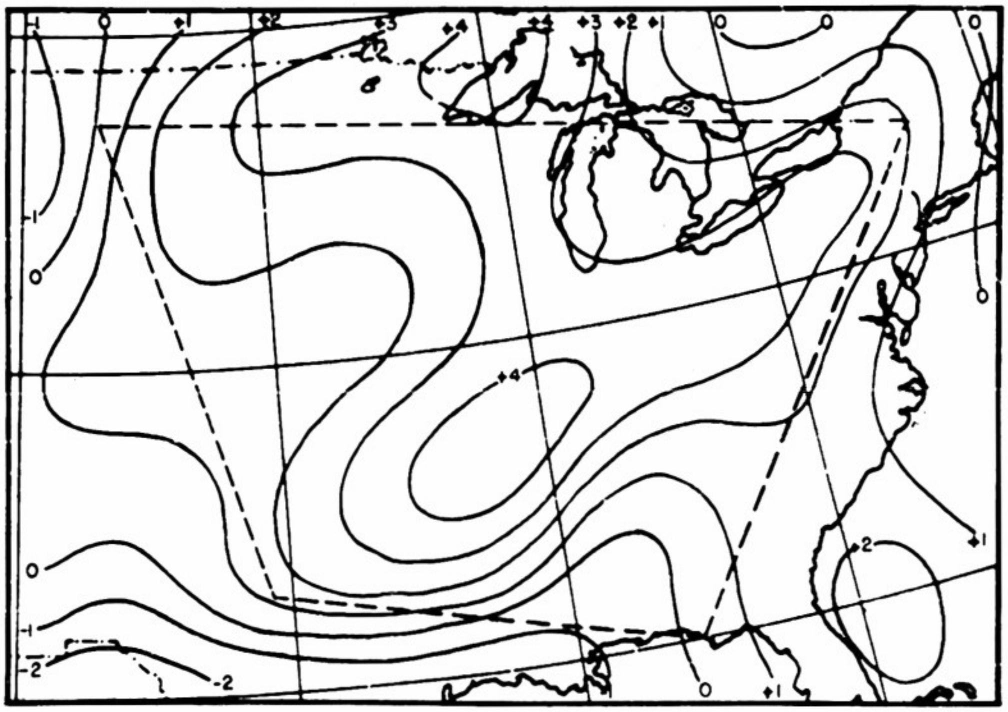

Figure 16. Advective direction tendency chart in units of 10°/6 hours.

thus extrapolated and forecast. This was adjusted to conform to the low winds in the south associated with the easternmost singular point. The speed gradient along the left hand normal of the jet in the South Dakota area was extrapolated and used as a guide in spacing forecast isovels. Finally it was noted that wind speeds under 25 kts were not reached immediately south of the Canadian border, and that a new speed maximum of uncertain position and magnitude seemed to be entering the area in the northwest. Most of these preliminary extrapolations appear on fig 13. Fig 14 is the resultant forecast map, and part of fig 4 is the verification map.

The major error in the test area of both of these prognostic charts is the forecast of the speed maximum found over New York at the time of the verification chart. This was an uncertain feature in the forecast. In figs 15 and 16 the advective tendency charts are shown. It will be seen that, had the speed-tendency chart been taken into account, the speed intensity would have been forecast to remain the same or increase slightly, and the direction of motion would have been retrograde to the northwest. Since the advective contributions to the tendency are probably larger than the actual tendencies, both the intensity and position might well have been held fixed. This would have improved the forecast.

5. SUMMARY AND CONCLUSIONS

The results have been largely negative. It was believed in the beginning that the wind fields themselves ought to enter directly into the wind prognosis and this belief is unchanged.

Unless some better technique of smoothing is used or unless the wind and pressure analyses are analysed together to minimise inconsistencies, the present upper wind network seems to be insufficient for the accurate determination of wind speed and direction tendencies. There is some indication, however, that the advective parts of these tendencies (which should be dominant) can be used in a qualitative way to improve the wind forecast since they showed general agreement with the forecast made using extrapolation methods and indicated an improvement in one region. It was found that the ageostrophic and vertical velocity contributions could not be measured accurately enough to be used in making a forecast. Clearly the motion of the wind field at a given level is in part determined by events in that level (the horizontal advective term is the major one here) and in part by linkage to events in other levels (the vertical advection and pressure terms are the major ones here). It would naturally be of interest to determine the relative order of magnitude of these two influences. Measurements of the vertical advection and pressure influence in this paper indicated larger or at least as large a contribution to the wind tendencies as the horizontal advection term which, if accepted, would indicate vertical linkage due to the ageostrophic and vertical velocity terms would be the controlling factor in the determination of wind field forecasts.

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